A Viscoelastic, Viscoplastic Model of Cortical Bone

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EXTENDED ABSTRACT

Cortical bone, as the principal structural component of the human body, functions in both a load-bearing and protective capacity. As a material, cortical bone has been the subject of mechanical investigation and characterization for well over a century, and the time dependent nature of this material’s mechanical response to loading is well documented. To model this time-dependent behavior, many researchers have employed a Voigt viscoelastic element [1,3,5], but this approach lacks the ability to predict bone’s material response in all but the most basic of loading conditions and has been shown invalid for strain rates ranging over more than a few orders of magnitude [2]. Furthermore, use of a Voigt element ignores viscoplastic behavior of the material entirely. In response to these shortcomings, the present study proposes a simple but accurate rate-dependant model that captures both the viscoelastic and viscoplastic components of cortical bone’s stress-strain behavior and is shown to be valid over a range of strain rates from 0.0001 s\(^{-1}\) to 1500 s\(^{-1}\).

The proposed model is divided into separate viscoelastic and viscoplastic deformation responses with each being concurrently driven by the overall stress state. New experimental data on the strain-rate sensitivity of cortical bone has been acquired using a Zwick/Roell Z010 materials testing machine at strain rates below 1 s\(^{-1}\) and an aluminum SHPB system at strain rates above 100 s\(^{-1}\). Examination of apparent elastic modulus as function of strain rate from this newly acquired data and previously reported values [1,4,5], has elucidated the existence of two separate strain-rate sensitivity regimes, which are captured in the proposed model by use of a Maxwell-Weichert element with two linearly viscoelastic branches. In addition, further examination of the new experimental data alongside the previously reported values of yield stress as a function of strain rate is shown to clearly demonstrate the applicability of the Ramberg-Osgood equation in characterizing the material’s viscoplastic behavior. The total material response of cortical bone prior to failure is thus expressed as a combination of both the viscoelastic and viscoplastic components. Validation of the proposed model is achieved by comparison to both the newly acquired experimental data and previously published results, such as those of McElhaney (1966) (Figure 1).

Figure 1: The stress-strain curves fits of the proposed model (solid lines) compared side-by-side with data points from McElhaney’s (1966) study on embalmed human femoral cortical bone (open circles).
REFERENCES


